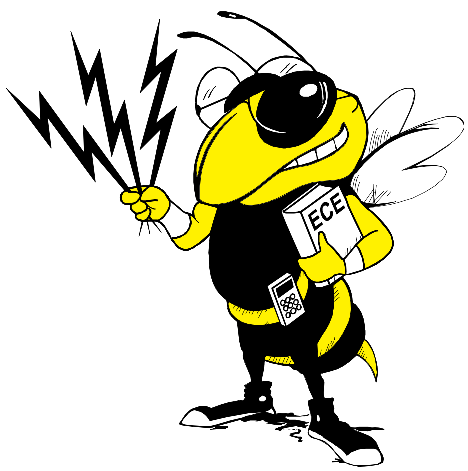
SiGe HBT BiCMOS Technology for Extreme Environment Applications

John D. Cressler

School of Electrical and Computer Engineering
791 Atlantic Drive, N.W.
Georgia Institute of Technology
Atlanta, GA 30332-0250 USA

cressler@ece.gatech.edu
Tel (404) 894-5161 / FAX (404) 894-4641
http://users.ece.gatech.edu/~cressler/



JPL Extreme Environment Workshop, 5/03

Outline

- Motivation
- Some Reminders on SiGe HBTs
- Operation at Extreme Temperatures
- Radiation Effects
- Summary

Communications Market

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- **Portable Communications Devices** (900 MHz to multi-GHz)
  - cellular phones, PDA, GPS, wireless internet, ...
- **Large Communications Platforms** (multi-GHz)
  - global links, radar systems, space-based services, …
- **Computer Links** (multi-GHz)
  - wireless LAN, optical fiber links, TV, internet, …
- **Transportation** (multi-GHz)
  - collision-avoidance radar, GPS, intelligent highway, …

Moral 1: **Frequency Bands are Pushing Increasingly Higher**

Moral 2: **Huge Market But Stringent Performance Requirements**

→ **We Need High-Speed + Low-Cost Device Technology!**

The Landscape

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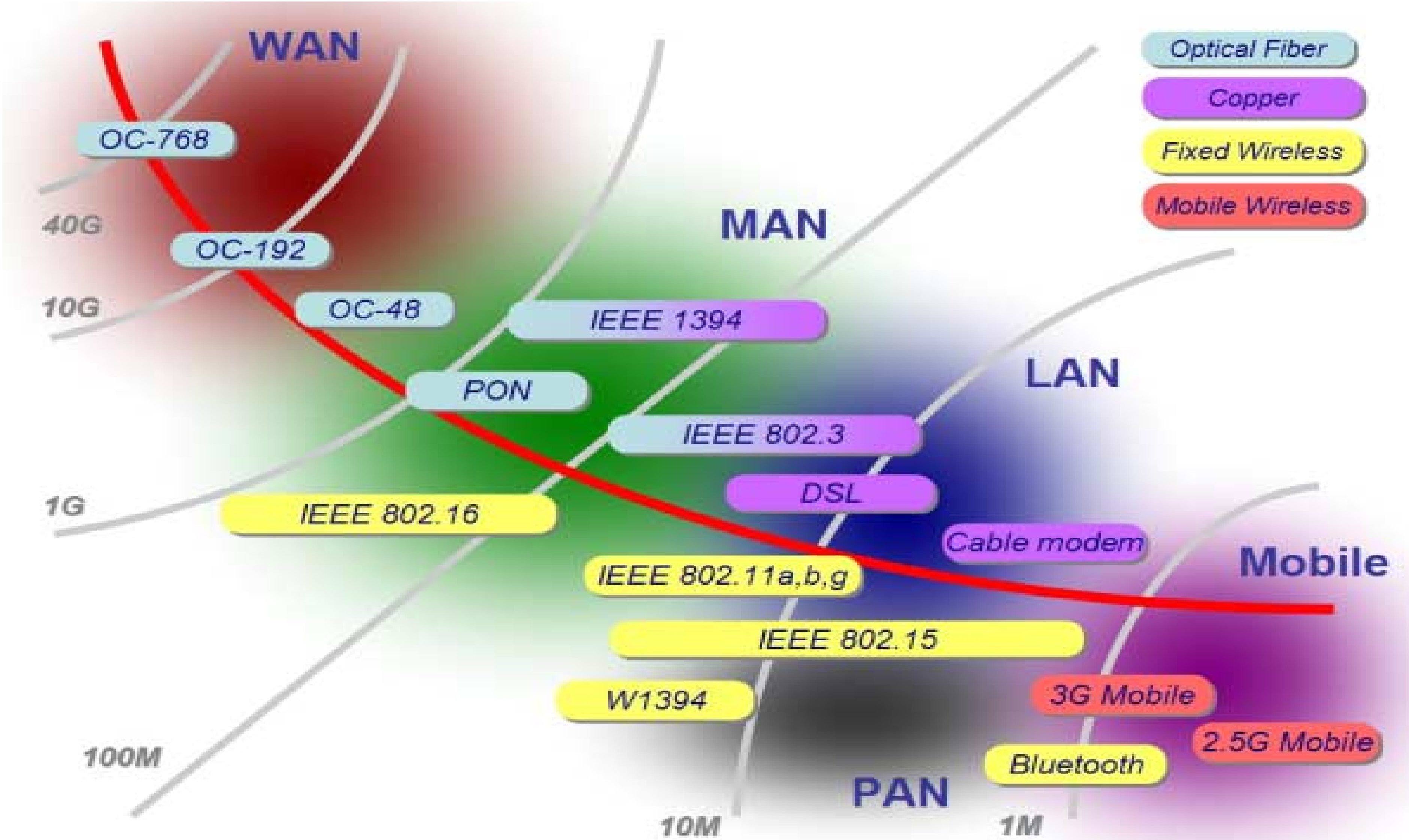

Courtesy of K. Lim

The Landscape

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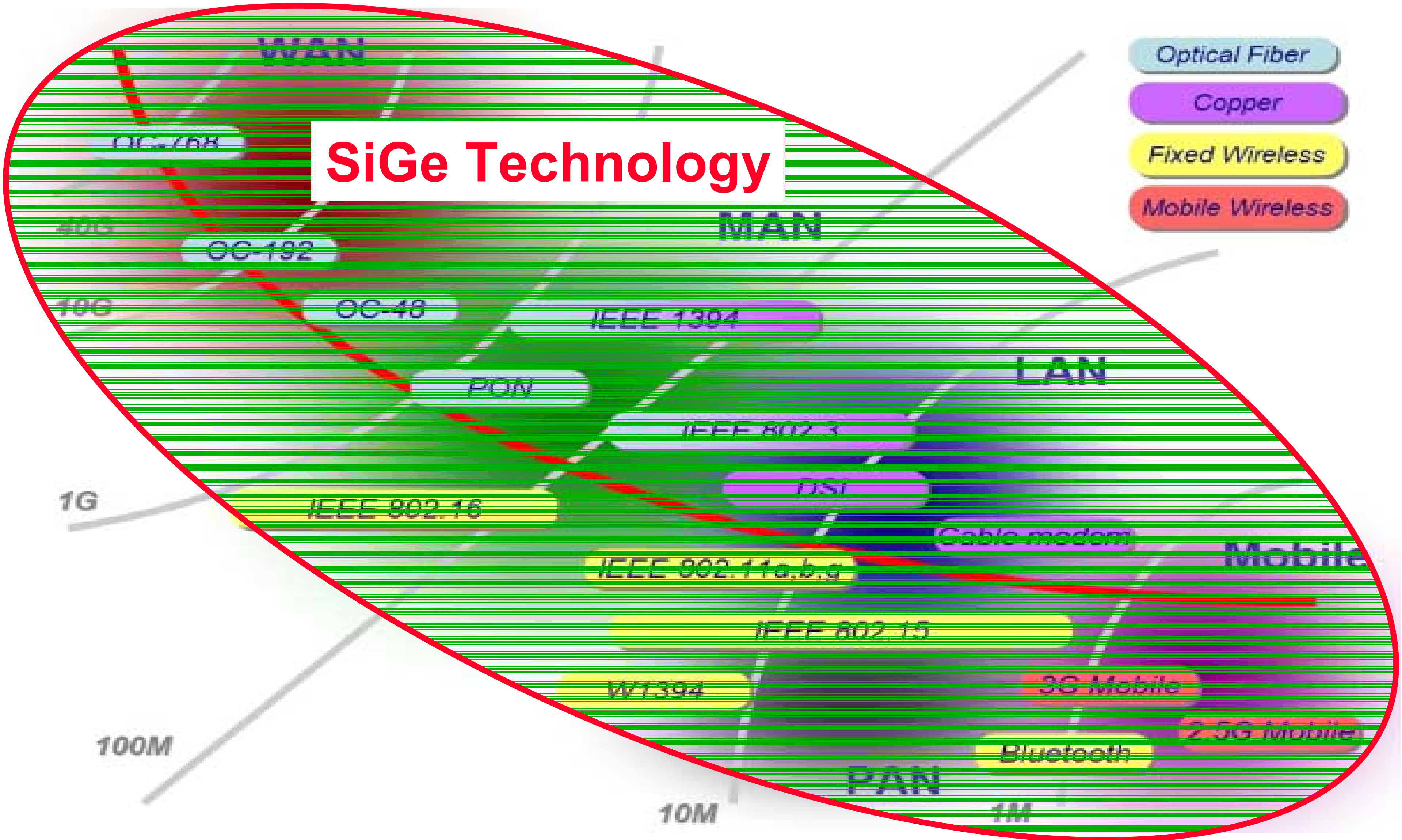
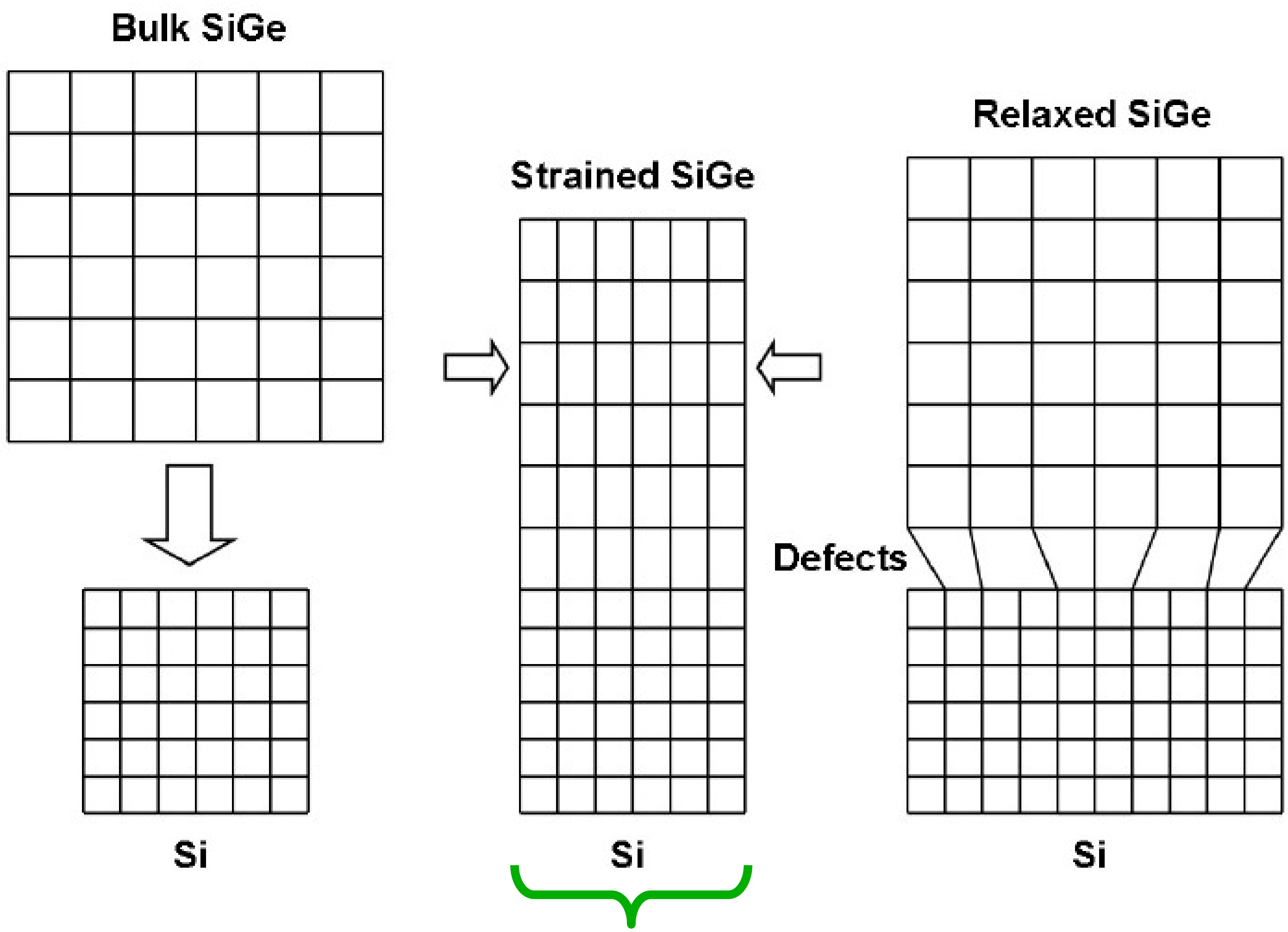


Courtesy of K. Lim

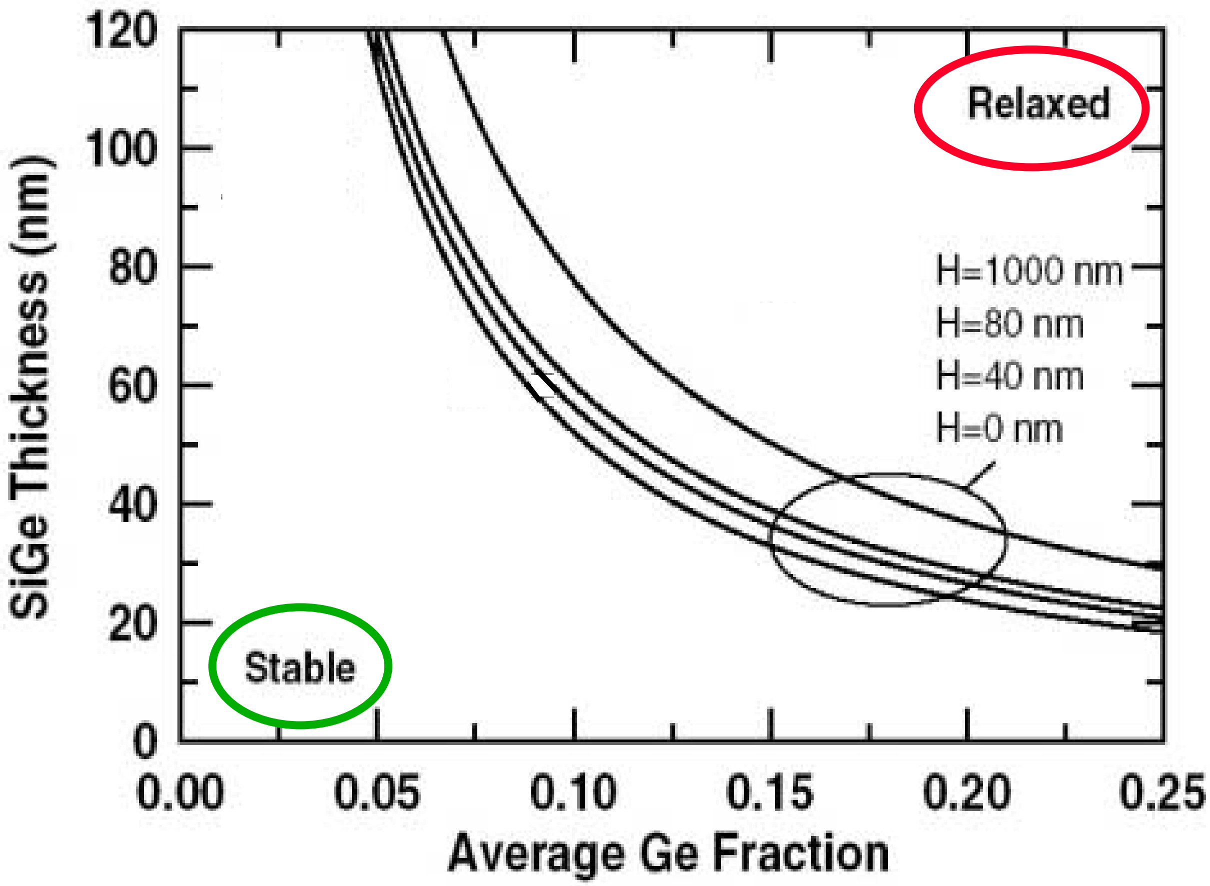
Strained-Layer Epitaxy

- **SiGe on Si → Compressive Strain in the SiGe Layer**



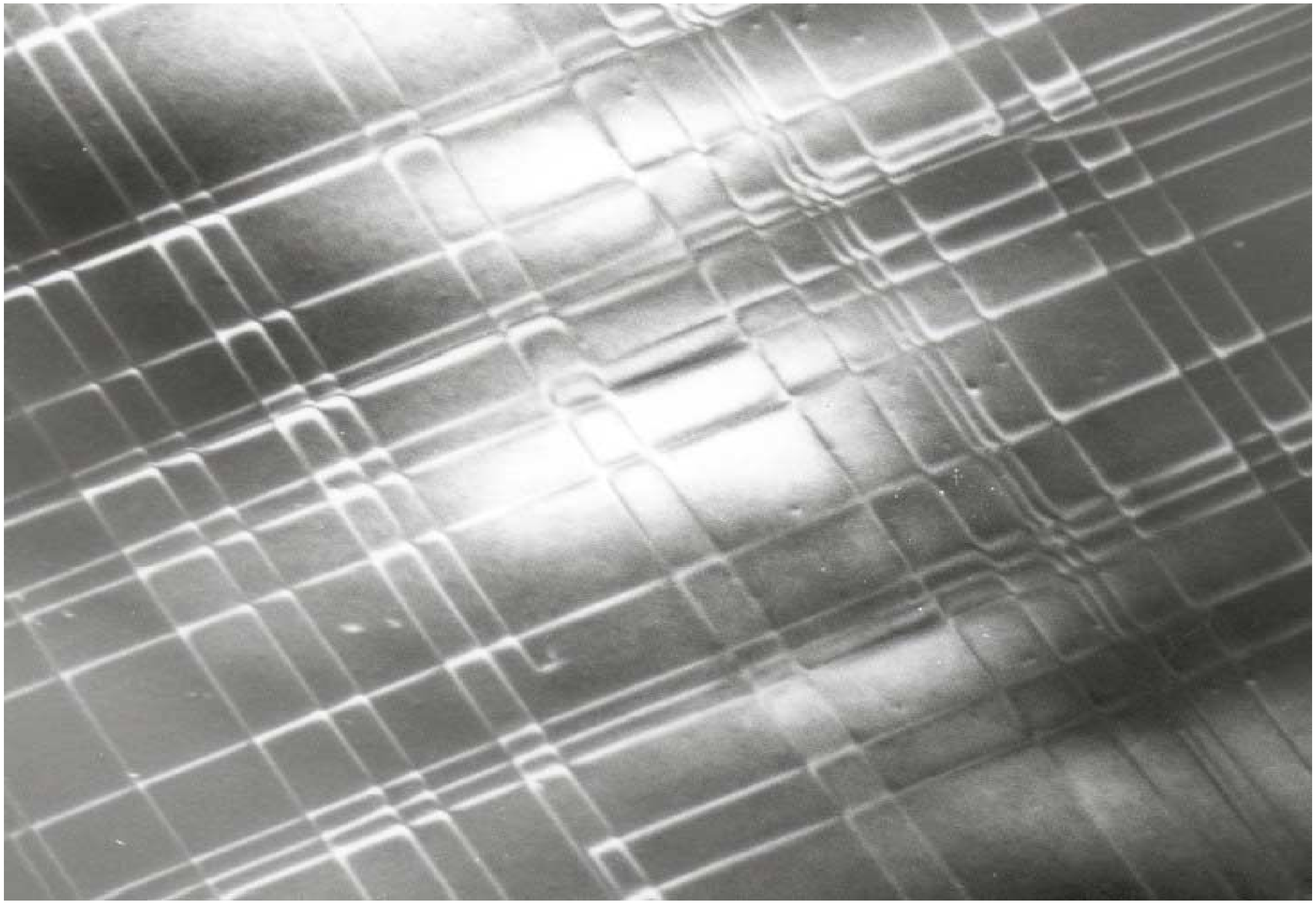
The Bad News …

- **Si and SiGe Are Not Lattice-Matched** (4% difference in lattice constant)
- **Places Stringent Restrictions on Film Stability** (% Ge + thickness)
- **<u>MUST</u> Avoid Film Relaxation** (defects)



Relaxation in SiGe

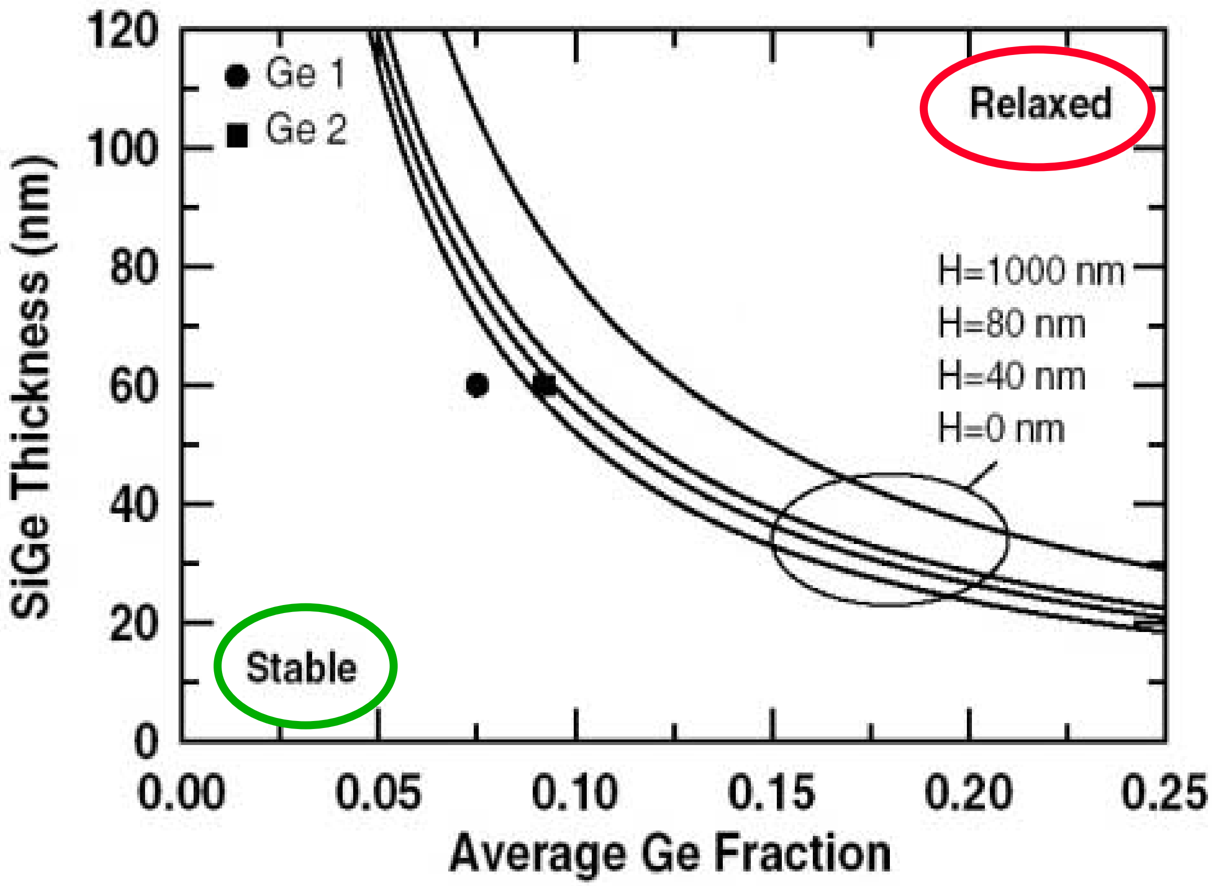
- **Relaxation Occurs Via Defect Formation … lots of defects!**
- **Bad News for Devices!**



Dislocation Structures in a Relaxed SiGe Film

The Good News …

- **Constraints Are "Easy" To Satisfy in Bipolar Transistors** (thin base)
- **Epitaxial Films Integrate With Conventional Si Processing** (CMOS)
- **Films are Amazingly Robust** (oxidation, implantation, etc.)



When You Do It Right …

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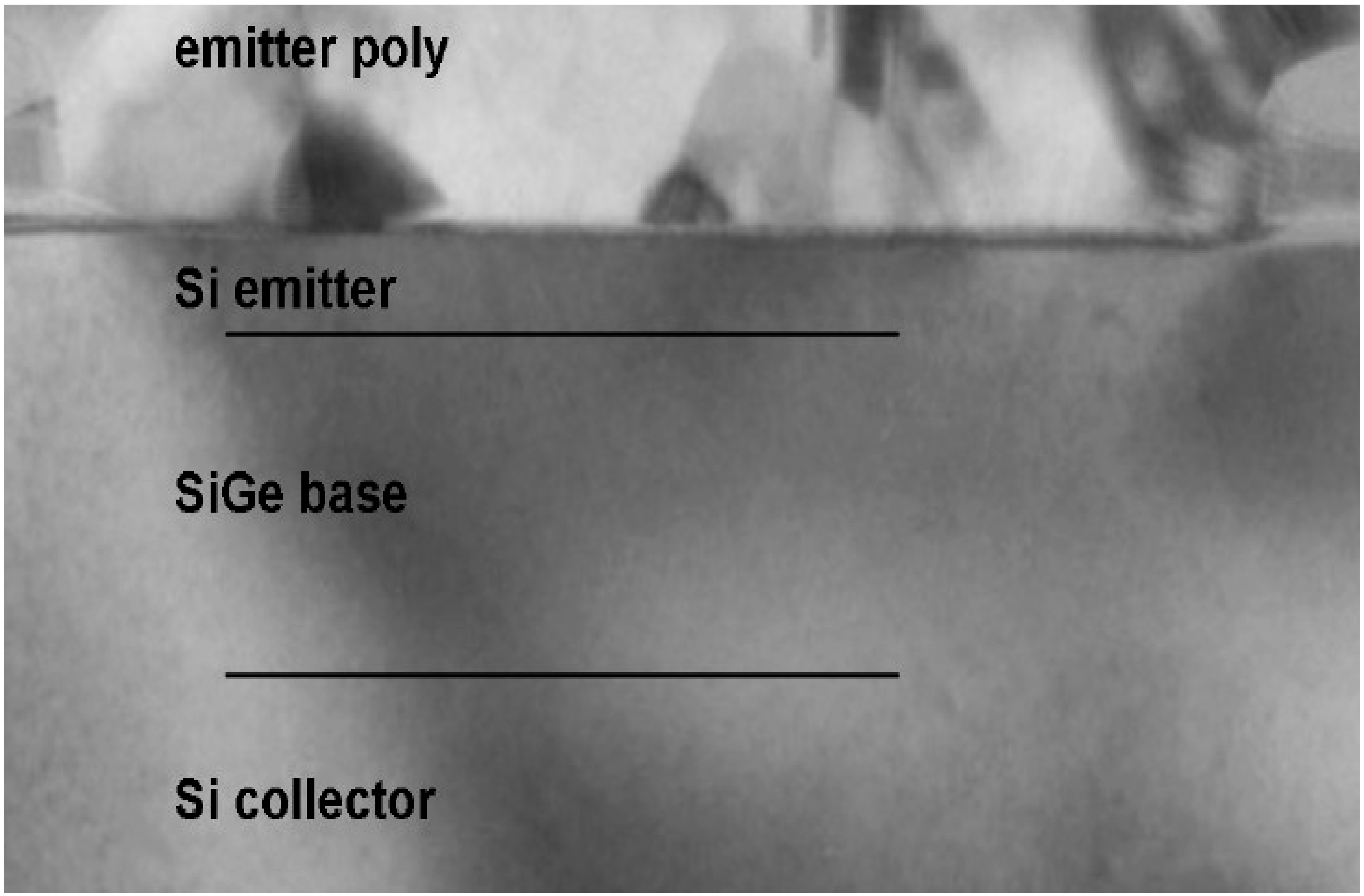
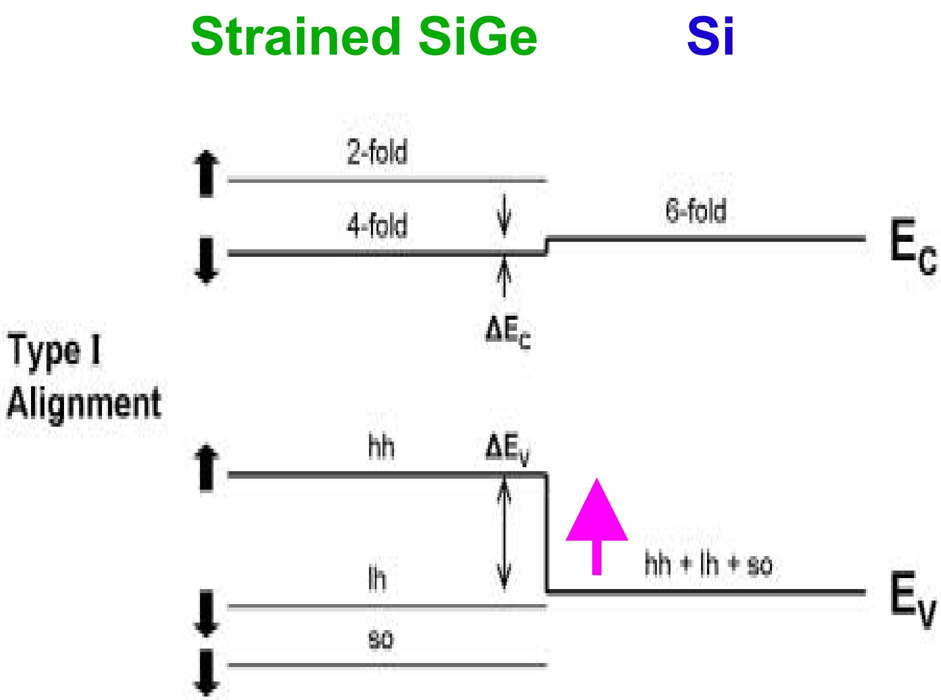
- **Seamless Integration of SiGe into Si**

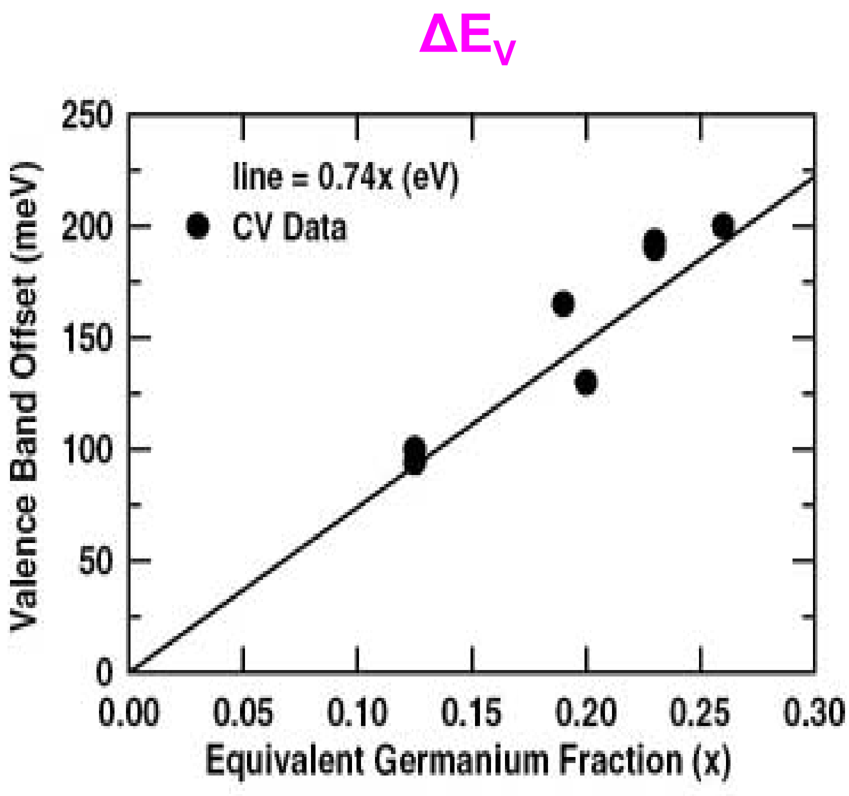


No Evidence of Deposition!

Electrical Consequences

- **Type-I Band Alignment** (Valence Band Offset = 74 meV / 10% Ge)
- **Strain-Induced Density-of-States Reduction** (bad news)
- **Hole Mobility Enhancement** (good news)





100 meV grading across 100 nm = 10 kV/cm electric field!

Device Cross-section

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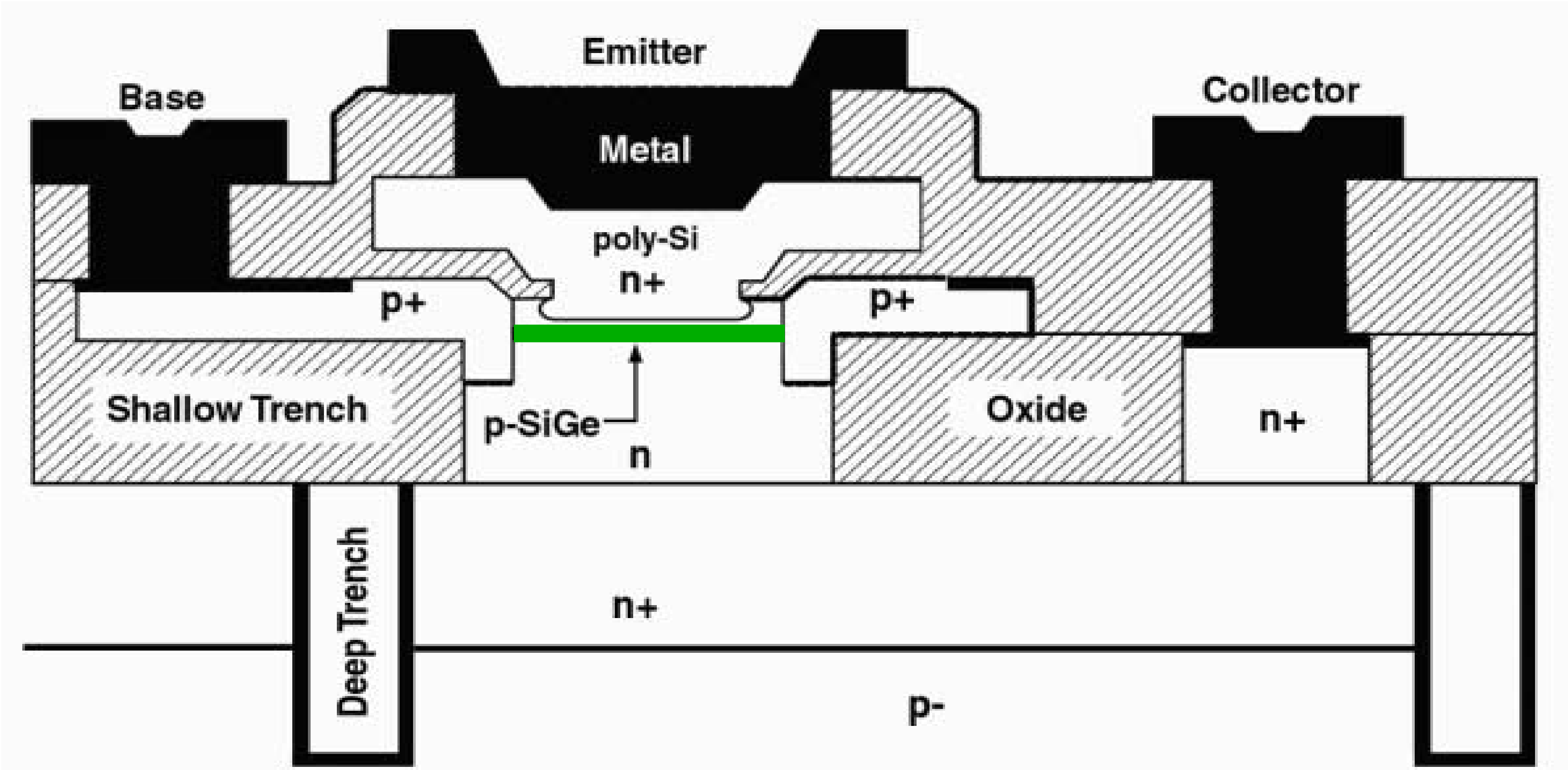
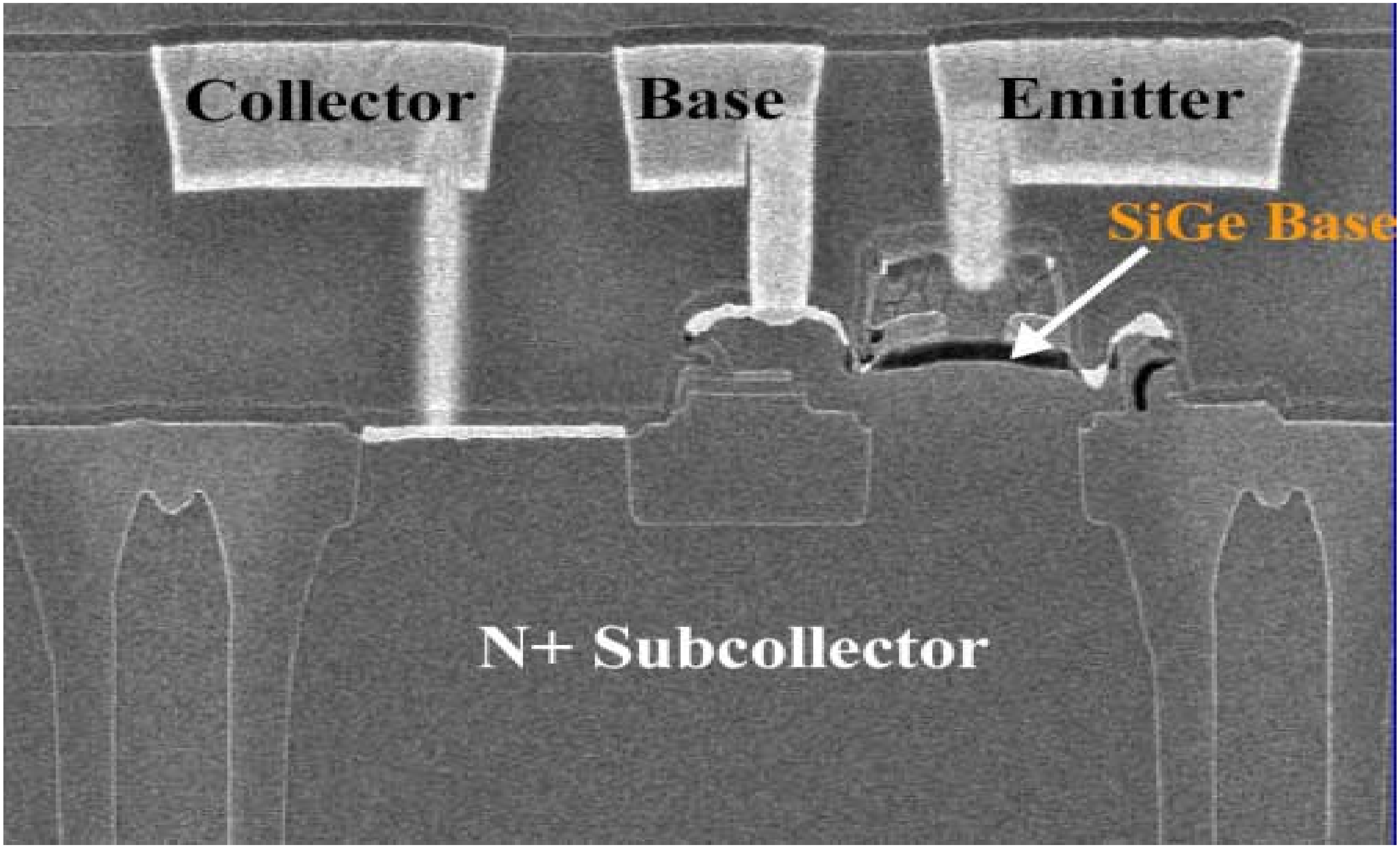
- **Conventional Shallow and Deep Trench Isolation + CMOS BEOL**
- **Unconditionally Stable UHV/CVD SiGe Epitaxial Base**
- **100% Si Fabrication Compatibility**



SEM of a SiGe HBT

- **120 GHz Peak f_T Process** (IBM)



Courtesy of IBM

Typical Doping Profile

1st Generation

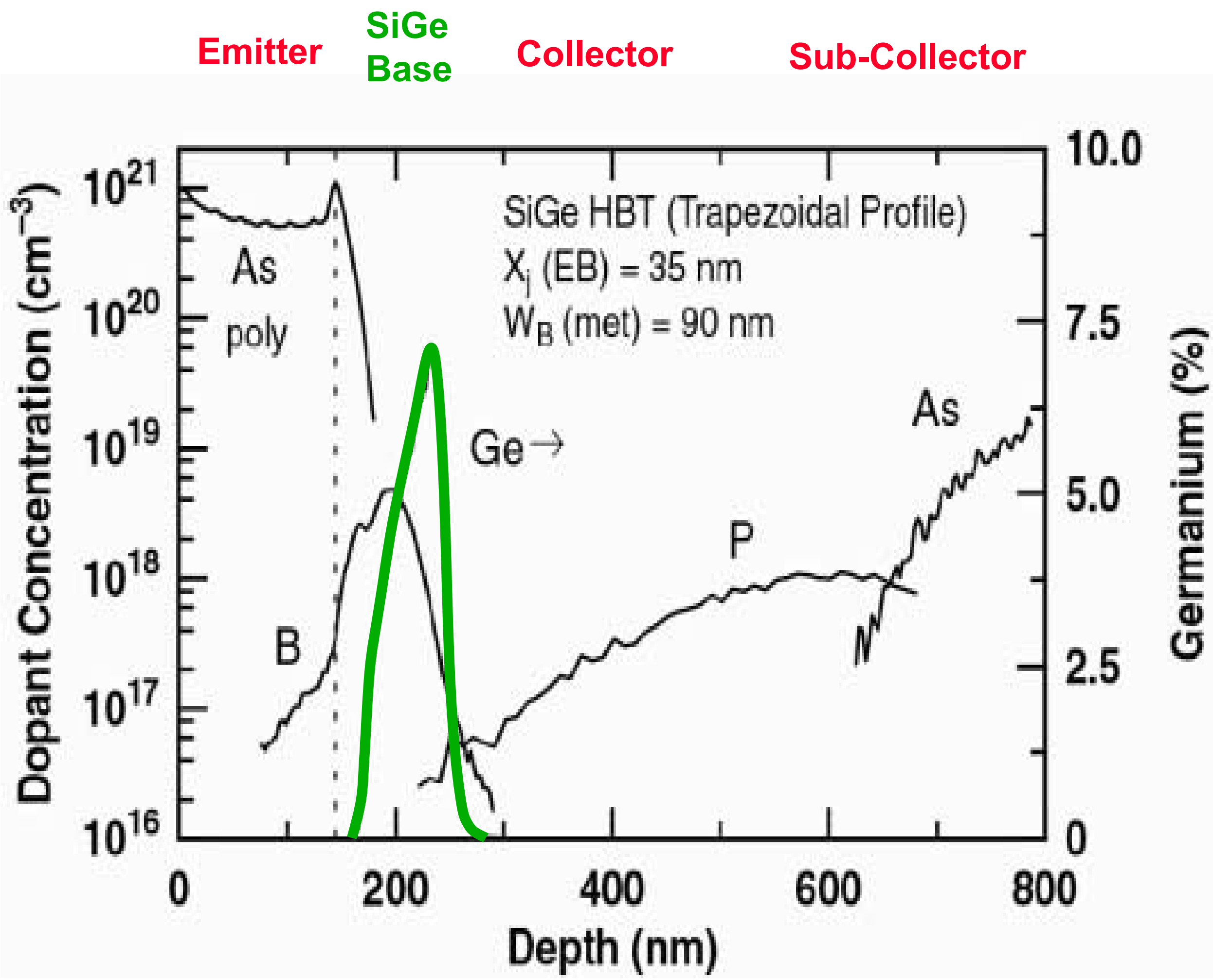
W_E (um)	0.42
peak f_T (GHz)	50
peak f_{max} (GHz)	70
BV_{CEO} (V)	3.3

2nd Generation

W_E (um)	0.18
peak f_T (GHz)	120
peak f_{max} (GHz)	100
BV_{CEO} (V)	2.5

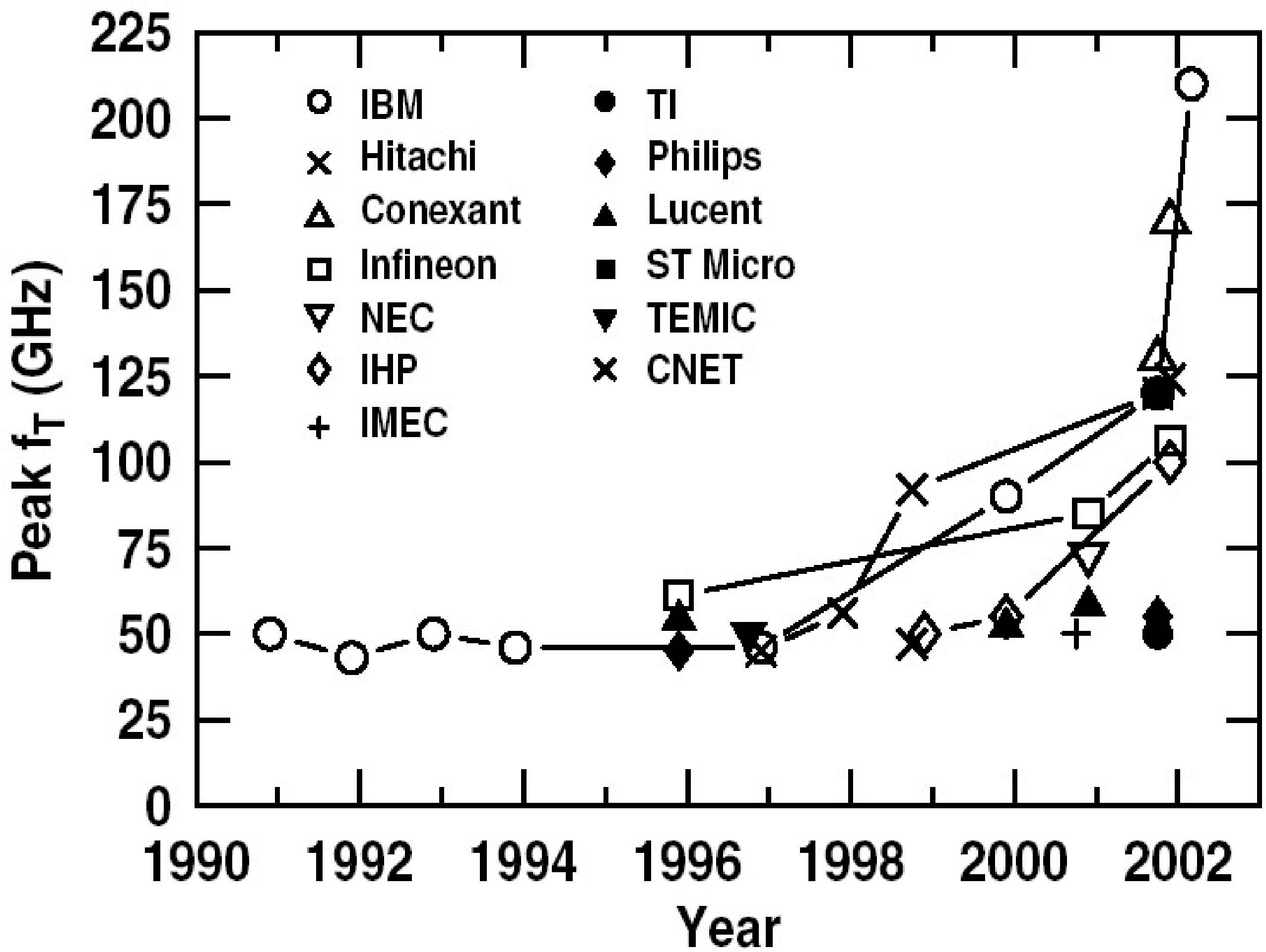
State-of-the-art

W_E (um)	0.12
peak f_T (GHz)	207
peak f_{max} (GHz)	285
BV_{CEO} (V)	1.7



Global SiGe Progress

• **Multiple Companies Are Working in the >100 GHz f_T Range**



SiGe BiCMOS Evolution

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- Best-of-Breed CMOS Comes Along for the Ride!
- Enables System-on-a-Chip Integration

SiGe HBT

Parameter	First	Second	Third
$W_{E,eff}$ (μm)	0.42	0.18	0.12
peak β	100	200	400
V_A (V)	65	120	> 150
BV_{CEO} (V)	3.3	2.5	1.7
BV_{CBO} (V)	10.5	7.5	5.5
peak f_T (GHz)	47	120	207
peak f_{max} (GHz)	65	100	285
min. NF_{min} (dB)	0.8	0.4	< 0.3

Si CMOS

Parameter	First nFET	First pFET	Second nFET	Second pFET	Third nFET	Third pFET
L_{eff} (μm)	0.36	0.36	0.14	0.15	0.092	0.092
V_{DD} (V)	3.3	3.3	1.8	1.8	1.5	1.5
t_{ox} (nm)	7.8	7.8	4.2	4.2	2.2	2.2
$V_{T,lin}$ (mV)	580	-550	326	-415	250	-210
$I_{D,sat}$ (μA/μm)	468	231	600	243	500	210

Technology Leverage

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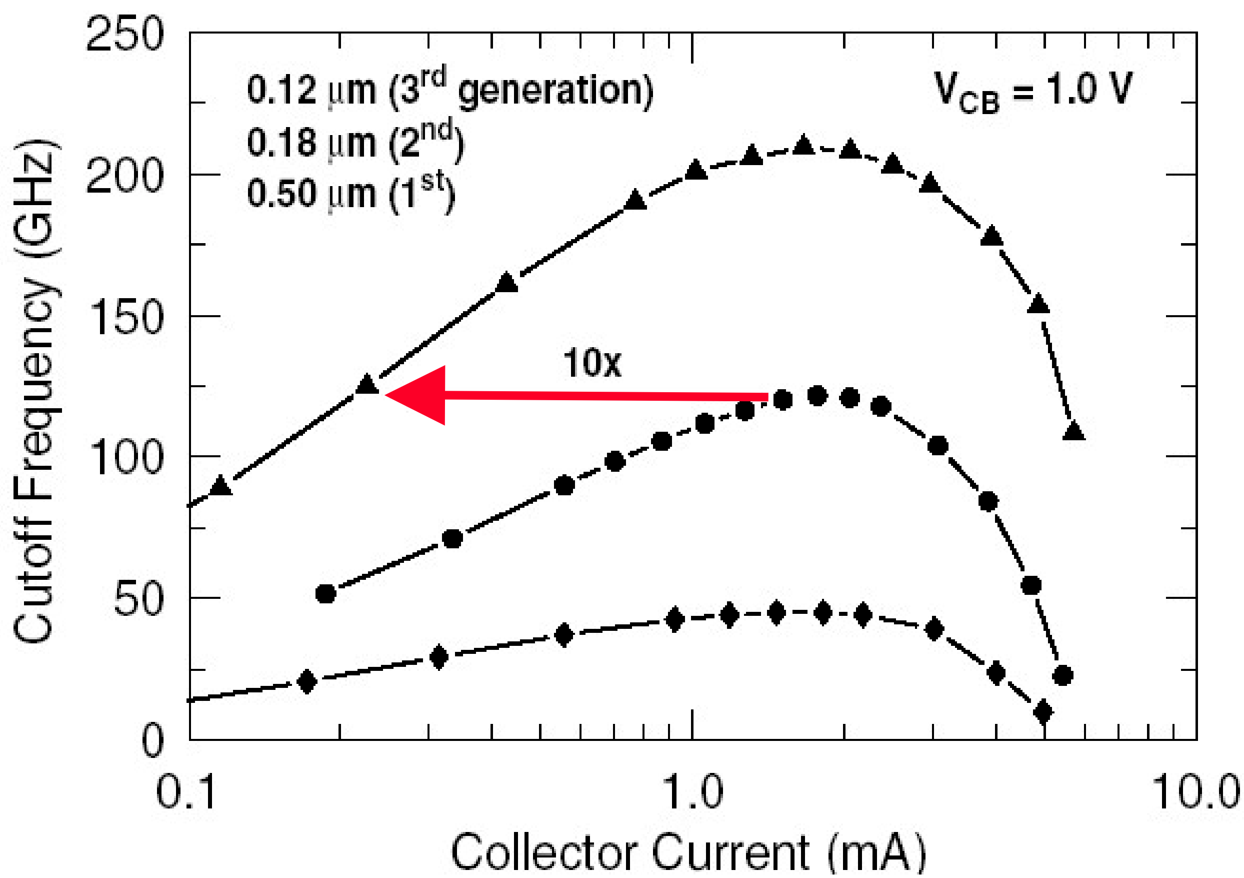
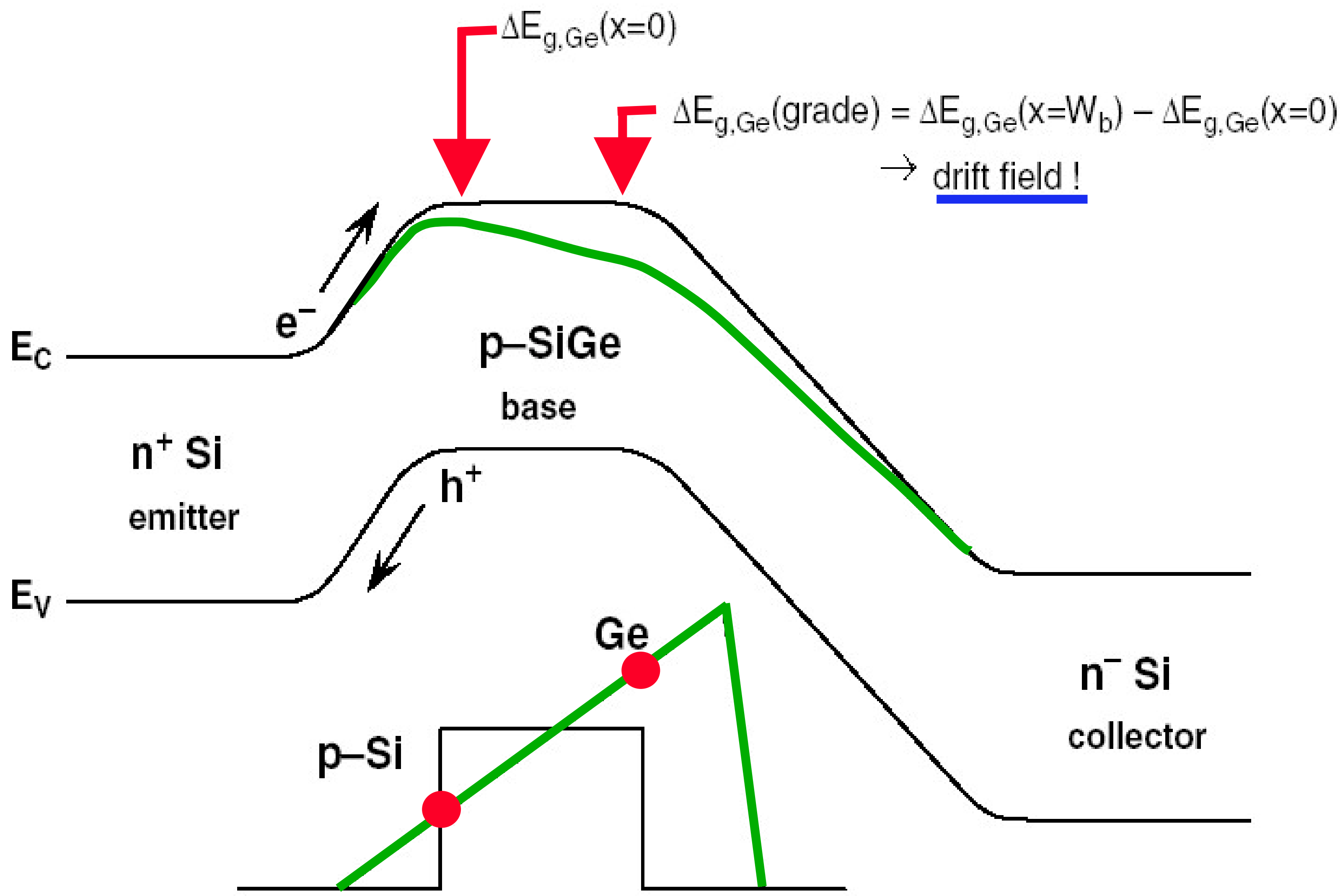
- **Si Has Come a Long Way!** (competitive with InP HBT technologies)
- **Substantial Power Savings Opportunities** (new system-level paradigm)
- **Maintains Si Economy-of-Scale**



Energy Band Diagram

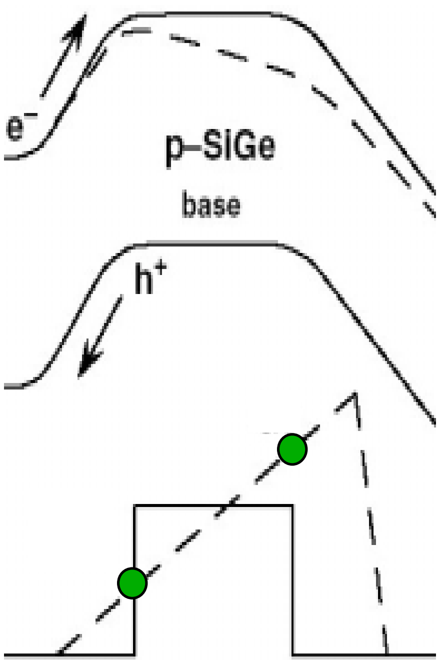


The SiGe HBT

The Idea: **Put Graded Ge Layer into the Base of a Si BJT**

Primary Consequences:

- **smaller base bandgap increases electron injection (β ⬆)**
- **field from graded base bandgap decreases base transit time (f_T ⬆)**
- **base bandgap grading produces higher Early voltage (V_A ⬆)**



$$\left.\frac{\beta_{SiGe}}{\beta_{si}}\right|_{V_{BE}} \equiv \Xi = \left\{ \frac{\tilde{\gamma}\,\tilde{\eta}\,\Delta E_{g,Ge}(grade)/kT\; e^{\Delta E_{g,Ge}(0)/kT}}{1 - e^{-\Delta E_{g,Ge}(grade)/kT}} \right\}$$

$$\frac{\tau_{b,SiGe}}{\tau_{b,Si}} = \frac{2}{\tilde{\eta}}\,\frac{kT}{\Delta E_{g,Ge}(grade)}\left\{1 - \frac{kT}{\Delta E_{g,Ge}(grade)}\left[1 - e^{-\Delta E_{g,Ge}(grade)/kT}\right]\right\}$$

$$\left.\frac{V_{A,SiGe}}{V_{A,Si}}\right|_{V_{BE}} \equiv \Theta \simeq e^{\Delta E_{g,Ge}(grade)/kT}\left[\frac{1 - e^{-\Delta E_{g,Ge}(grade)/kT}}{\Delta E_{g,Ge}(grade)/kT}\right]$$

➡ **III-V HBT Properties + Si Processing Maturity!**
Bandgap Engineering in Si!

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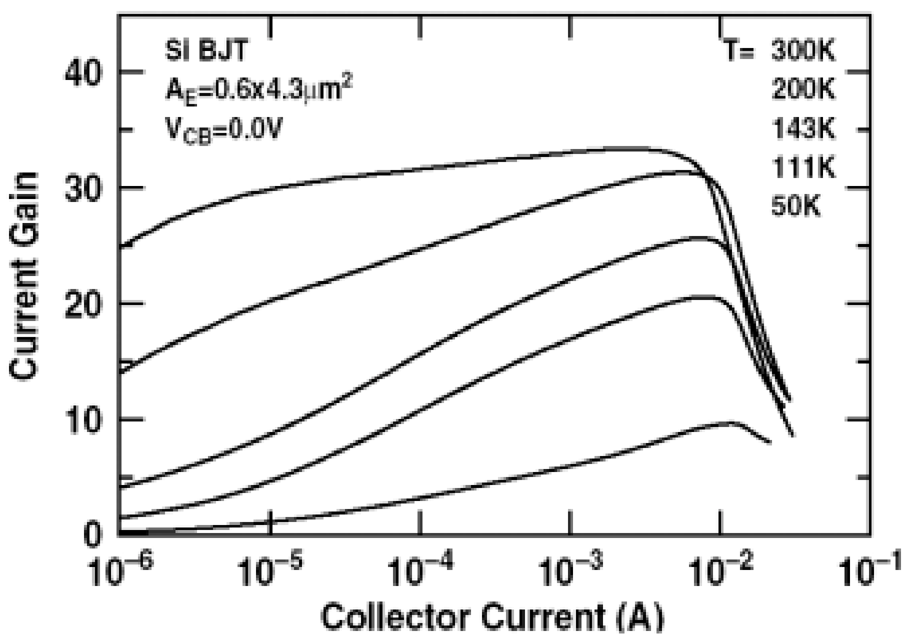
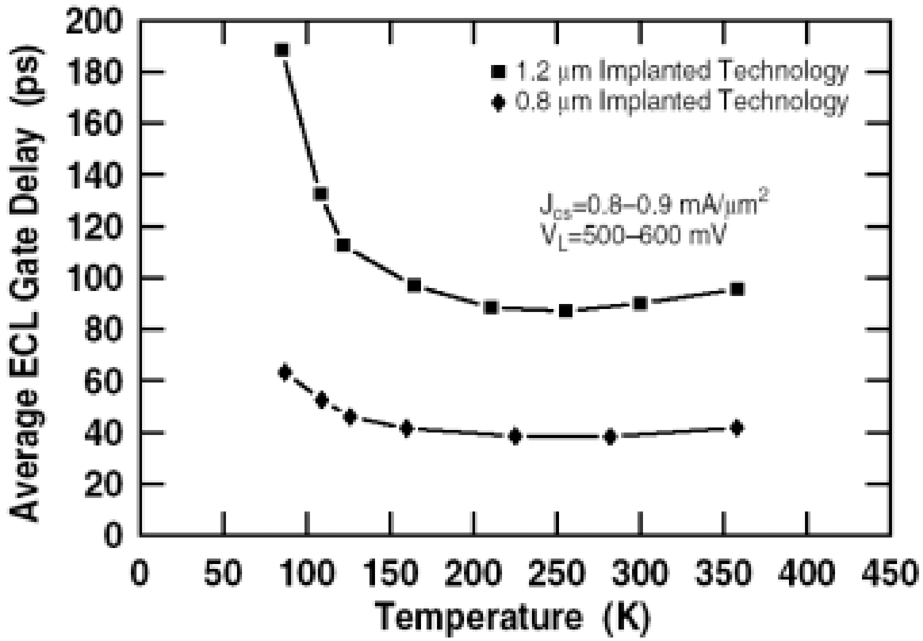
Si BJTs at Cryo-T

- **Degradation in Current Gain with Cooling (bad news)**
  - driven by emitter-to-base bandgap narrowing differences
- **Degradation in Speed with Cooling (bad news)**
  - driven by diffusivity decrease in base transit time and base freeze-out





$$\beta_{ideal}(T) = \frac{q D_{nb}(T)\, L_{pe}(T)\, N_{de}^{+}(T)}{D_{pe}(T)\, W_b(T)\, N_{ab}^{-}(T)}\, e^{(\Delta E_{gb}^{app} - \Delta E_{ge}^{app})/kT}$$

$$\tau_{b,Si}(T) = \frac{W_b{}^2(T)}{2 D_{nb}(T)} = \frac{q W_b{}^2(T)}{2\, kT\, \mu_{nb}(T)}$$

SiGe HBTs at Cryo-T?

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Primary Consequences:

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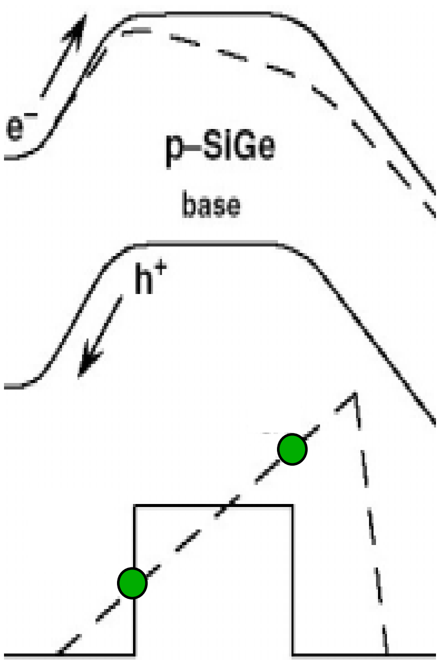
- **base bandgap grading produces higher Early voltage** **(V_A ⬆)**



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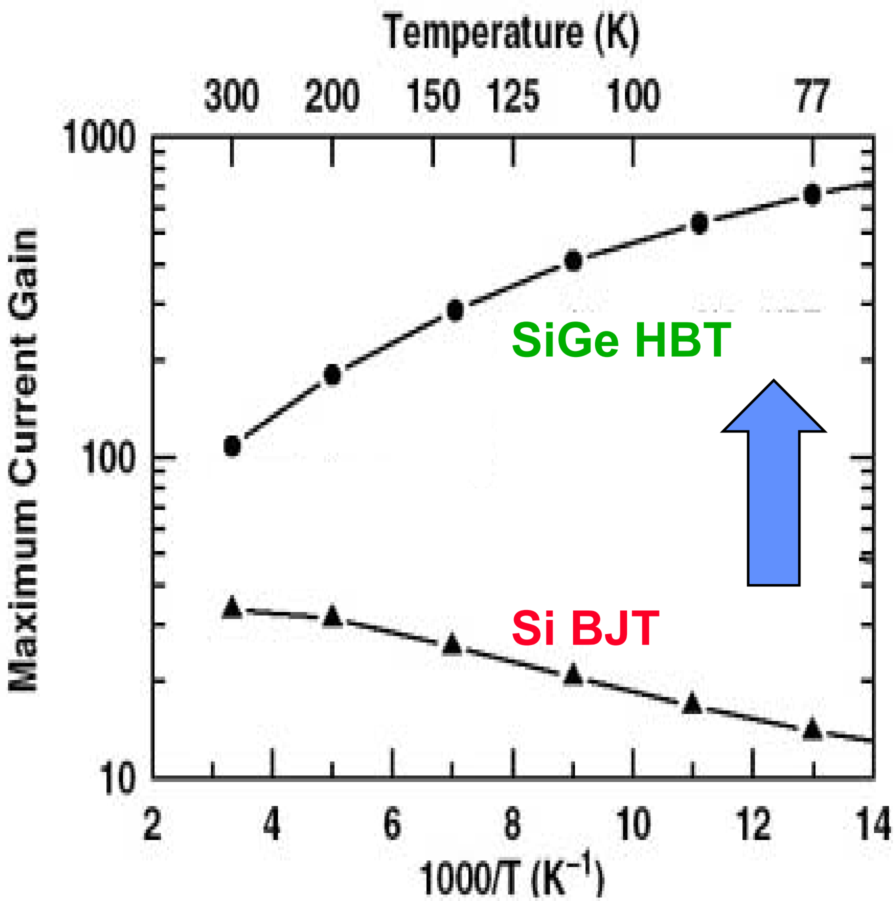
$$\frac{\tau_{b,SiGe}}{\tau_{b,Si}} = \frac{2}{\tilde{\eta}}\,\frac{\underline{kT}}{\Delta E_{g,Ge}(grade)}\left\{1 - \frac{\underline{kT}}{\Delta E_{g,Ge}(grade)}\left[1 - e^{-\Delta E_{g,Ge}(grade)/\underline{kT}}\right]\right\}$$

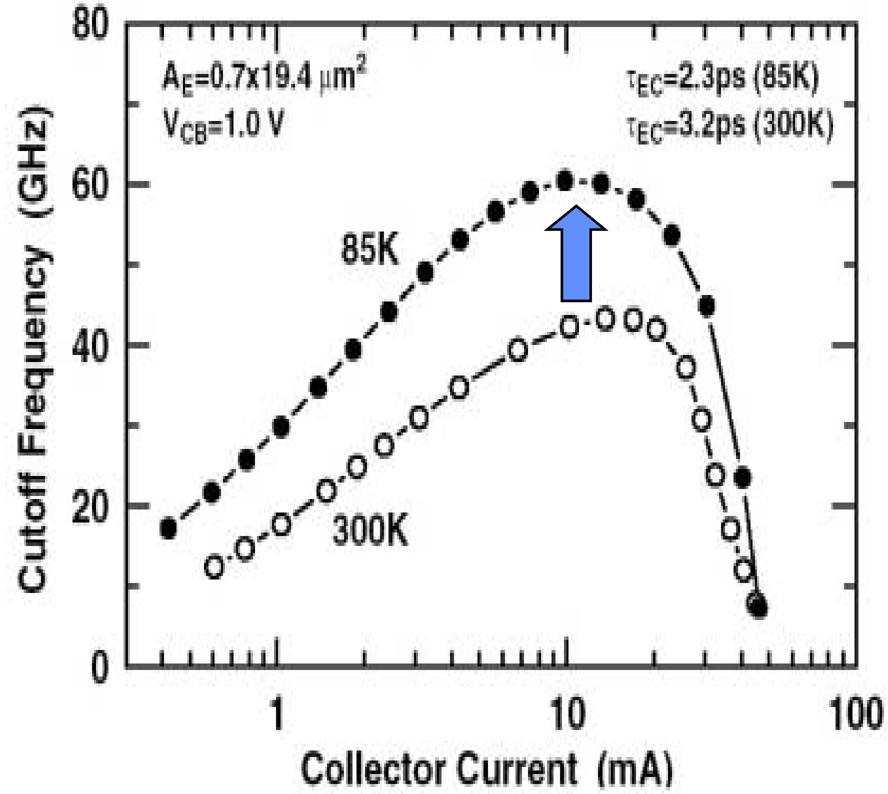
$$\left.\frac{V_{A,SiGe}}{V_{A,Si}}\right|_{V_{BE}} \equiv \Theta \simeq e^{\Delta E_{g,Ge}(grade)/\underline{kT}}\left[\frac{1 - e^{-\Delta E_{g,Ge}(grade)/\underline{kT}}}{\Delta E_{g,Ge}(grade)/\underline{kT}}\right]$$

→ **All kT Factors Are Arranged to Help at Cryo-T!**

Device Characteristics

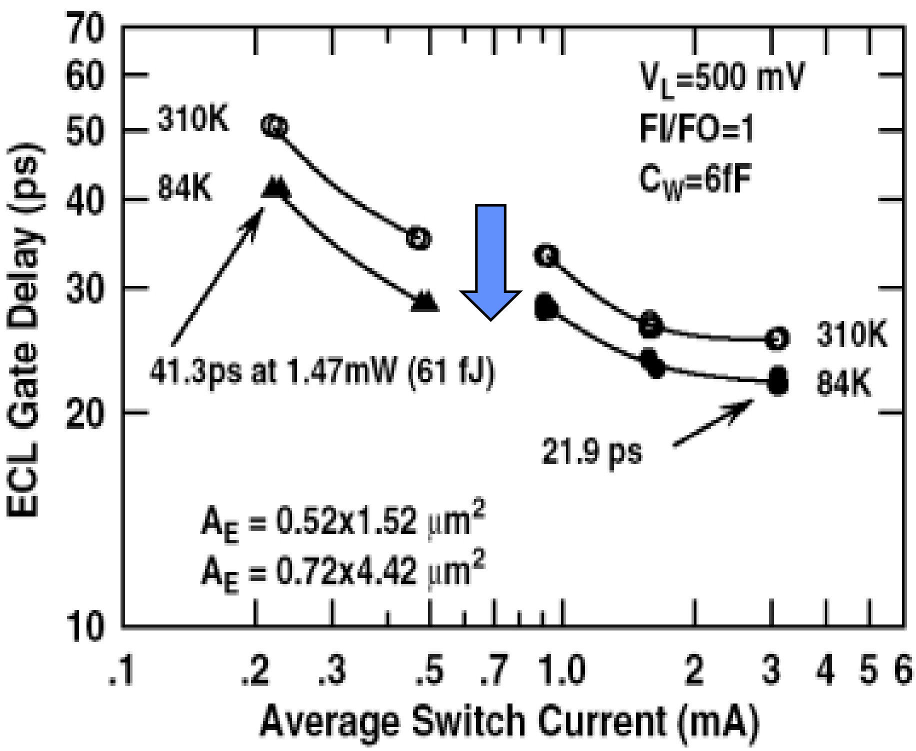
- **SiGe Performance Improves With Cooling (good news)**
  - current gain and output resistance (Early Voltage) increases with cooling
  - frequency response / noise improve with cooling
  - abrupt, heavily doped epitaxial base controls freeze-out





Digital Circuits

- **SiGe Enables High-Speed Circuits at Cryogenic Temperatures**
  - frequency response improves with cooling
  - abrupt, heavily doped epitaxial base controls freeze-out
  - higher large-signal g_m allows reduced logic swing operation



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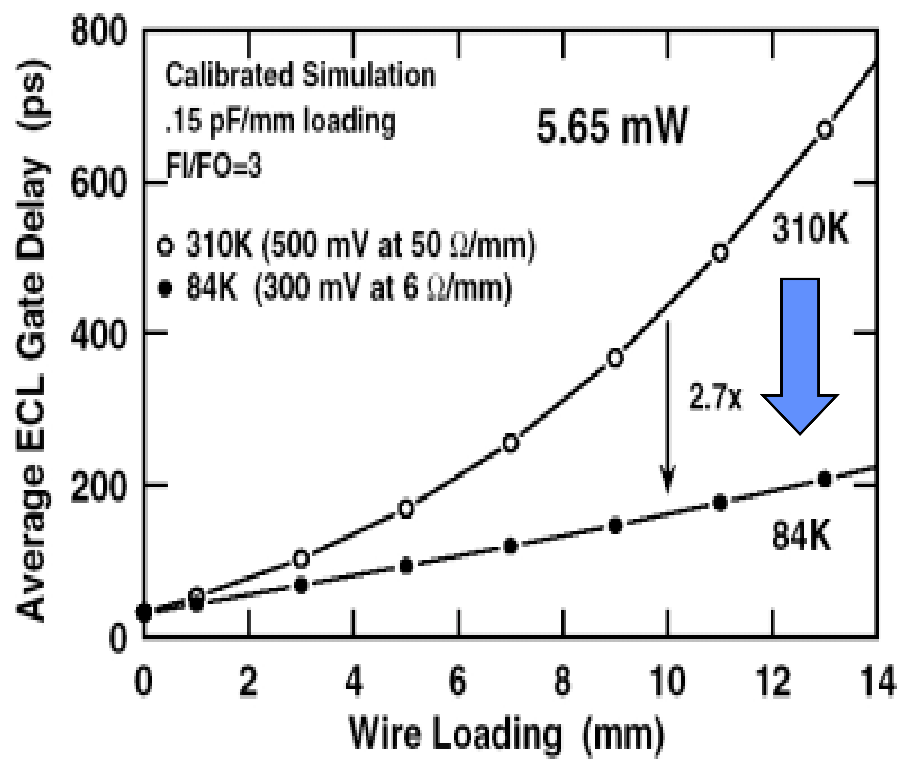

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Recent Cryo-T Results

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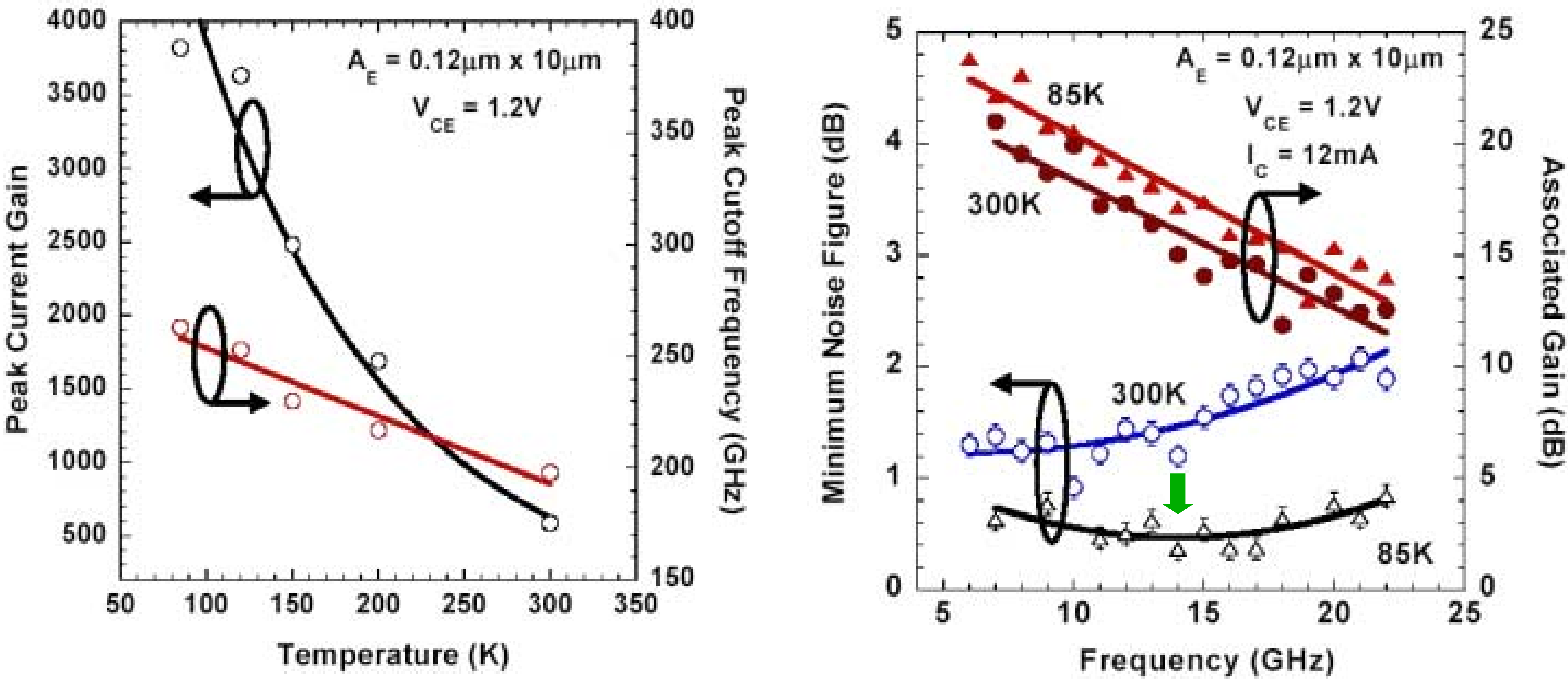
- 200 GHz SiGe Technology Works VERY Well at 77K
- At 85K, f_T > 250 GHz and NF_{min} = 0.30 dB with G_{ass} = 17 dB at 14 GHz!



Best-of-Breed RF/microwave/mm-wave Circuits at Cryo-T!

Helium Temperature?

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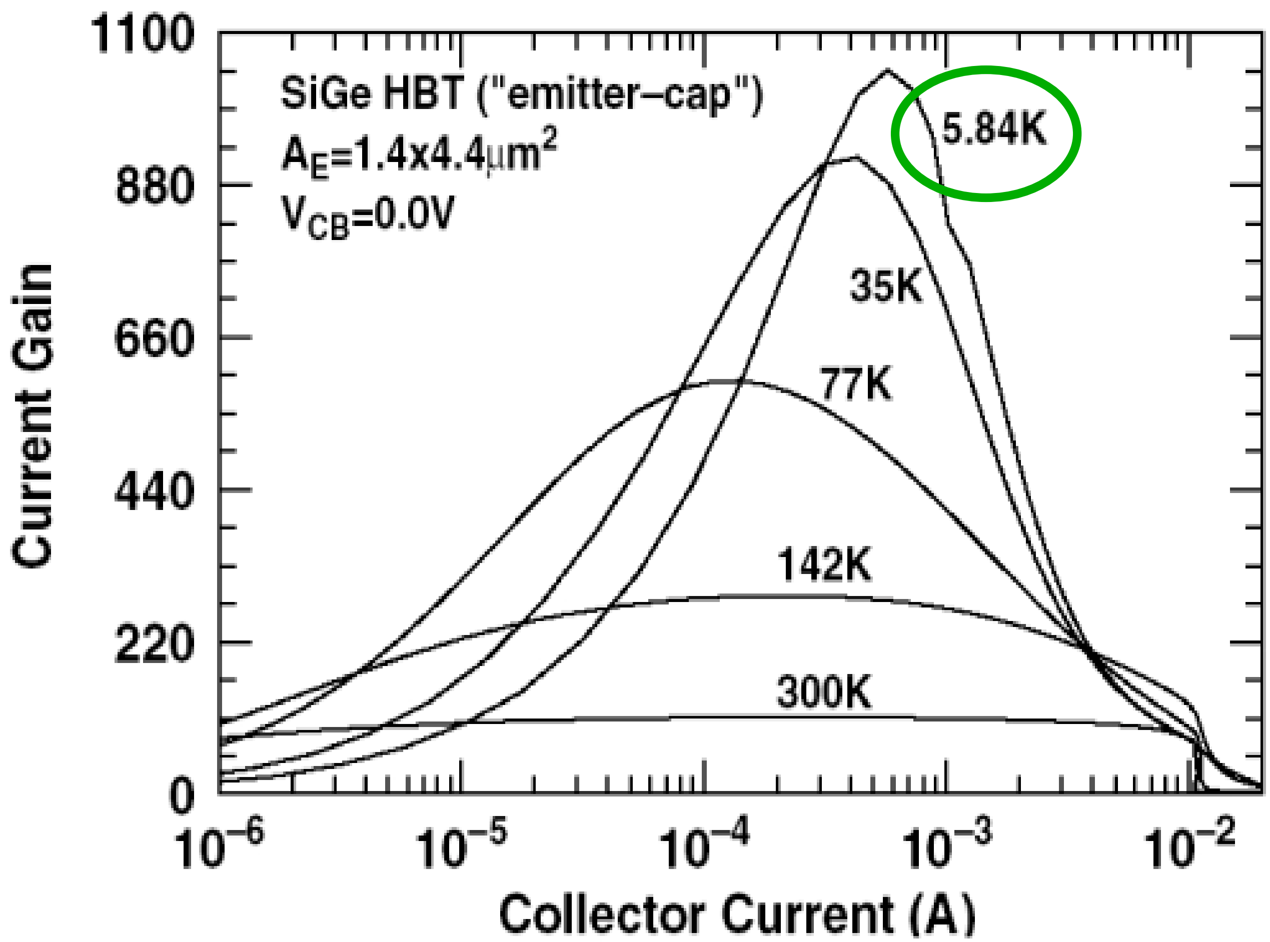
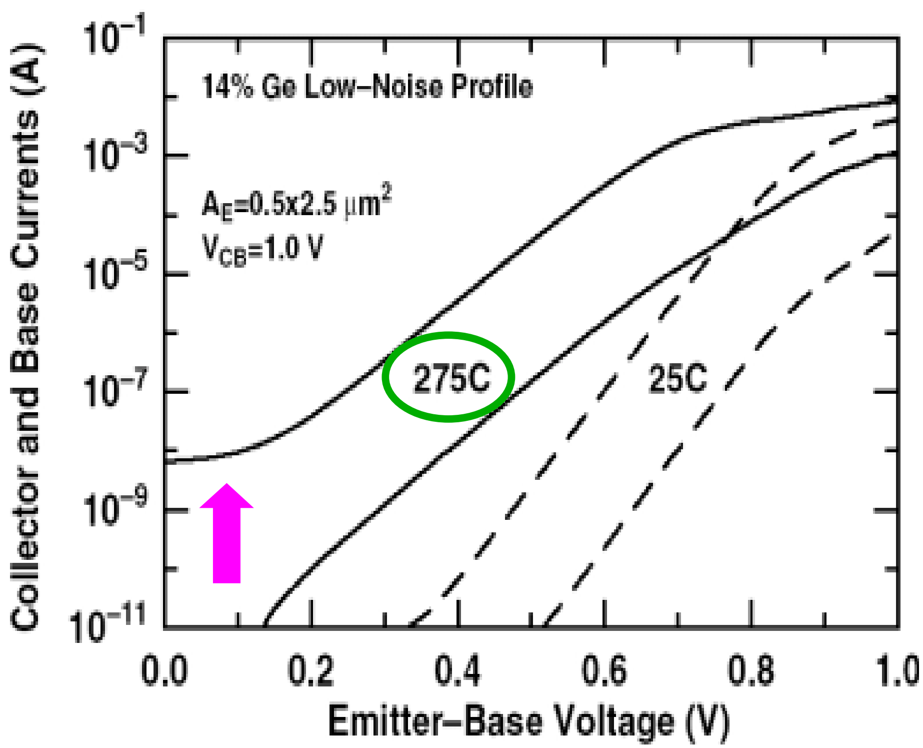
- **SiGe Is Clearly Capable of Operation Down to the Helium-T Regime**
  - base doping is above Mott transition – minimal base freeze-out
  - more work needed to flesh out the HeT design/operation space

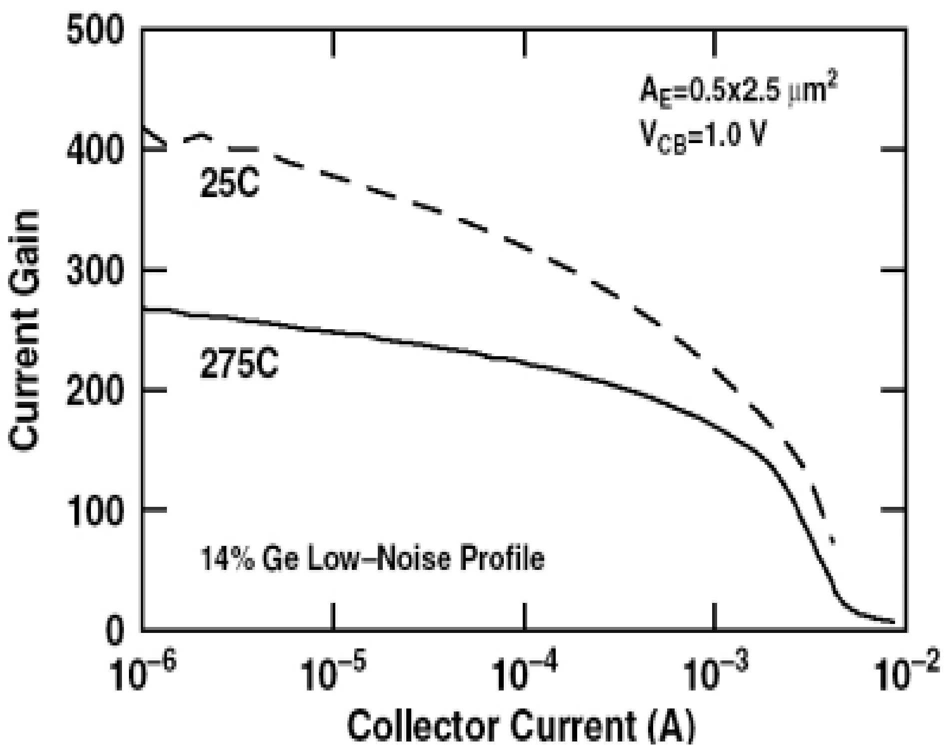


1st Generation SiGe HBTs

High Temperatures?

- **SiGe Operates Well Up to at Least 300C**
  - minimal CB leakage + adequate current gain (some *ac* degradation expected)
  - Ge profile can be optimized for high-T if necessary
  - SiGe on SOI is also a valid technology path if required





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Radiation Effects

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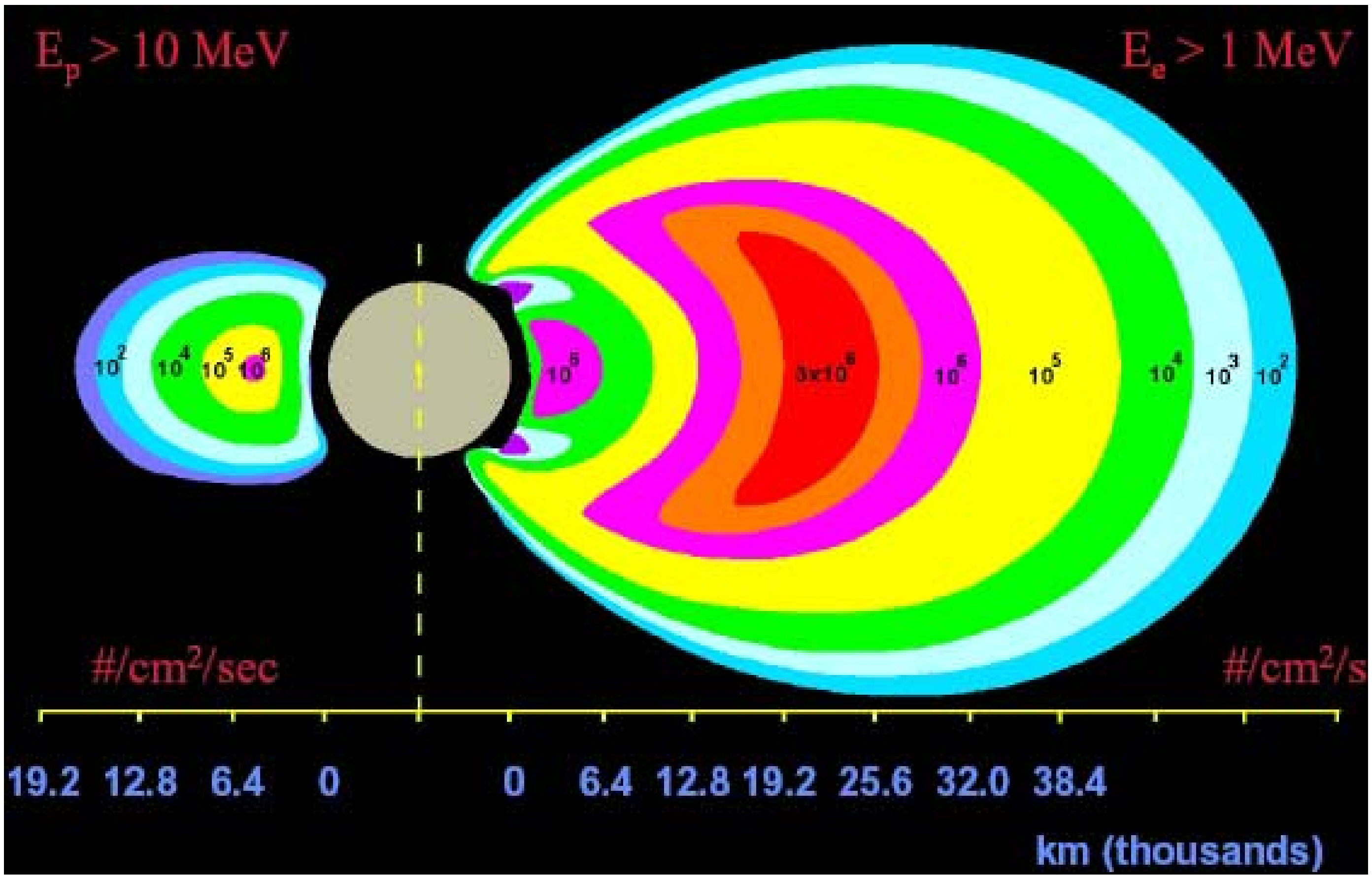
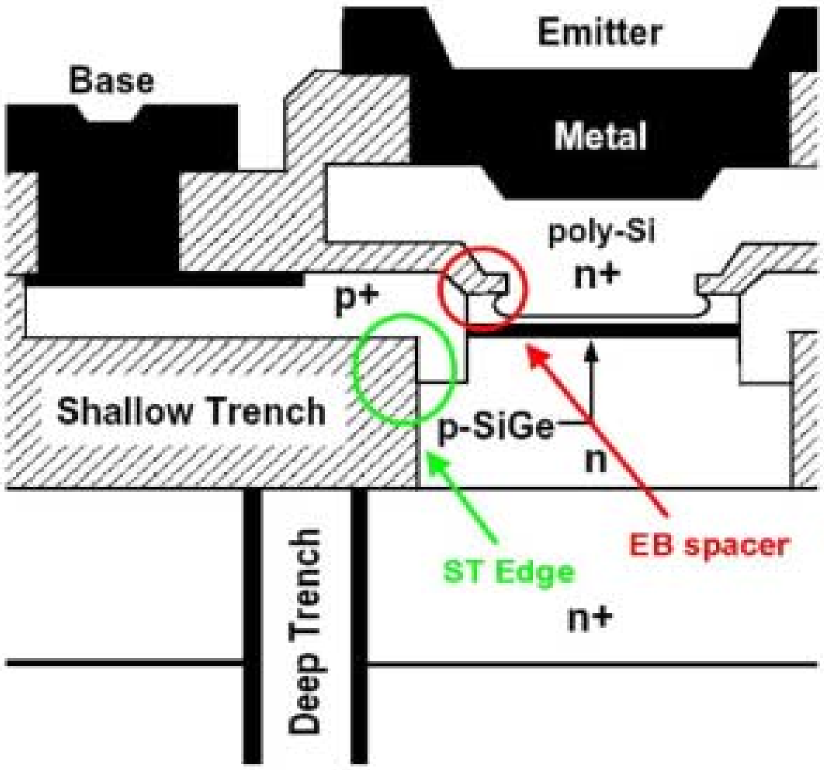
- **The Holy Grail of the Space Community**
  - IC technology space-qualified **without** additional hardening

proton belts **electron belts**



Experiments (1995-2003)

- **SiGe HBT BiCMOS Technology Generations:**
  - 1st Generation (IBM 5HP – 50 GHz HBT + 0.35µm CMOS)
  - 2nd Generation (IBM 6HP – 50 GHz HBT + 0.25µm CMOS)
  - 3rd Generation (IBM 7HP – 120 GHz HBT + 0.18µm CMOS)
  - 4th Generation (IBM 8HP – 200 GHz HBT)
- **Radiation Sources:**
  - gamma rays
  - protons (1.75 MeV to 200 MeV)
  - neutrons
  - low dose rate gamma
  - gamma at 77K
- **Single Event Effects:**
  - heavy ion
  - proton
  - ion microbeam



Recent Results

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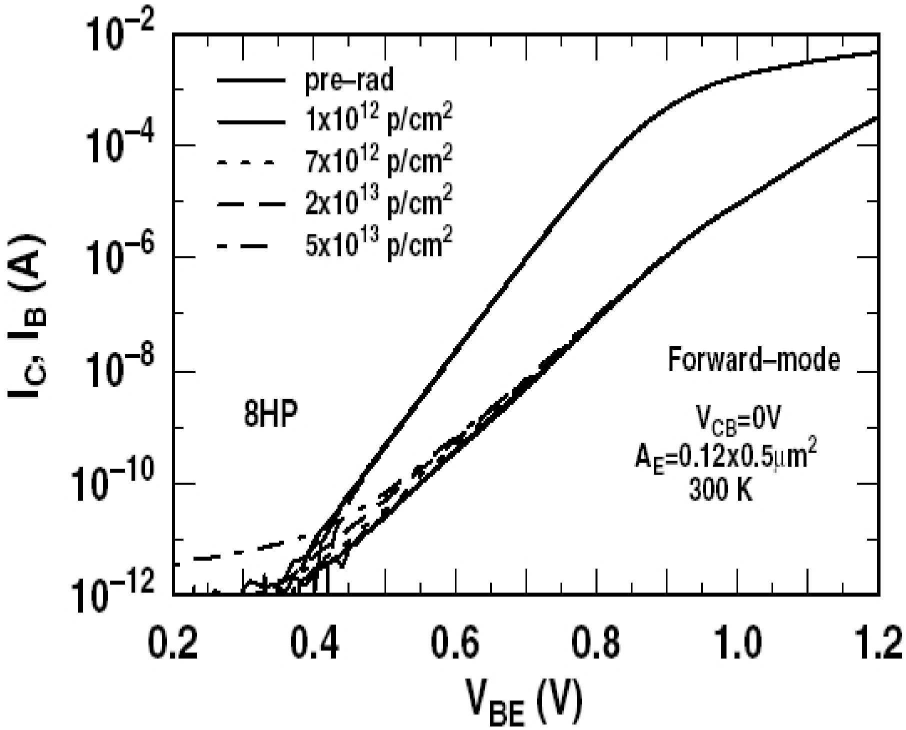
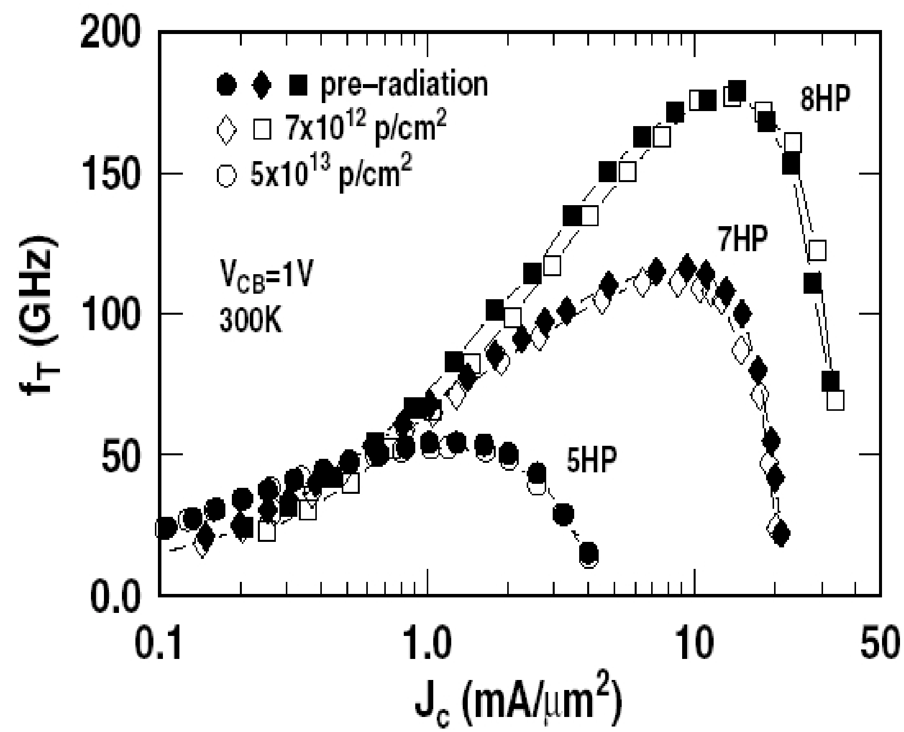
- **Multi-Mrad Total Dose Hardness (with no intentional hardening!)**
- **Radiation Hardness Due to Epitaxial Base Structure (not Ge)**
  - thin emitter-base spacer + heavily doped extrinsic base + very thin base





63 MeV protons

Radiation + Cryo?

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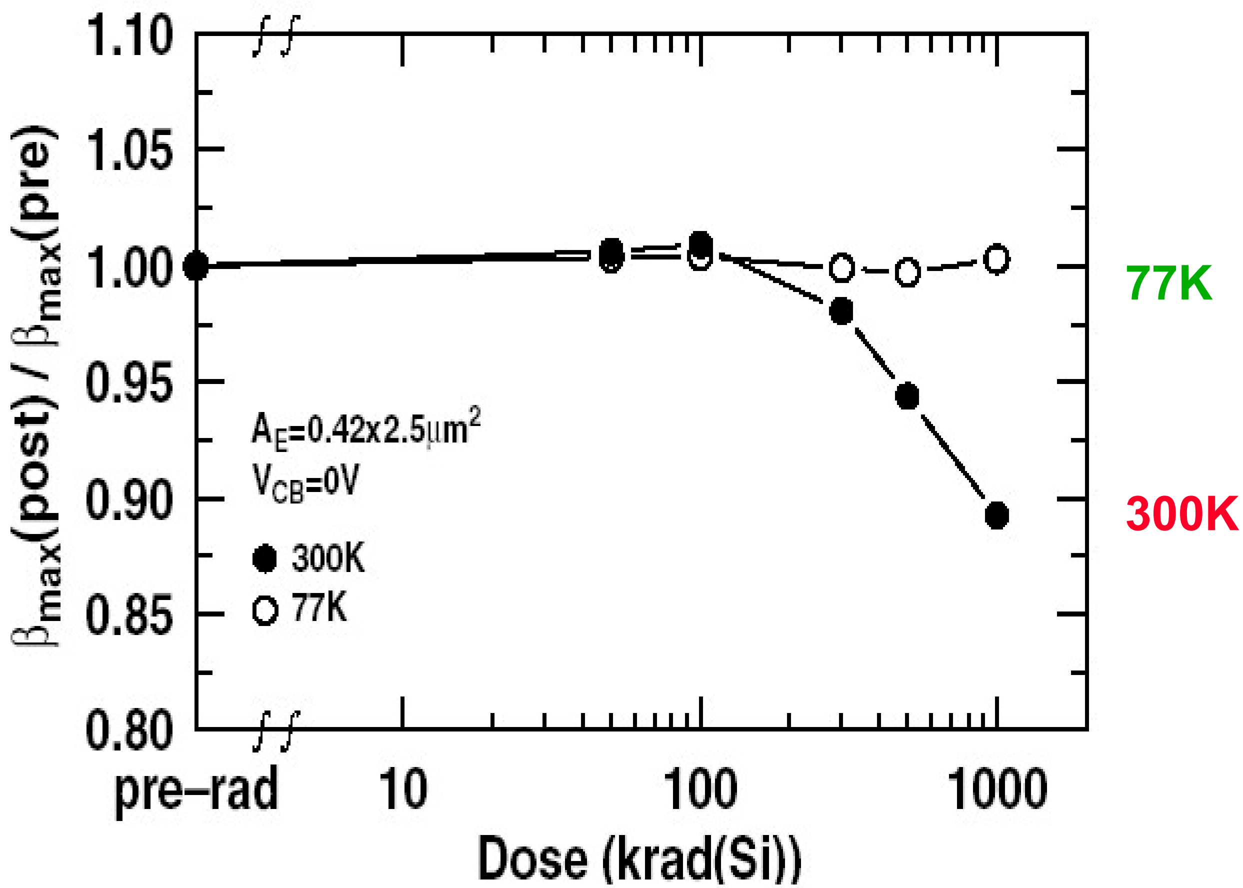
- **Compare Total Dose Tolerance Between 300K and 77K**
- **77K Gamma Irradiation**
  - even less damage than at 300K!



Summary

- **SiGe HBT BiCMOS Technology**
  - bandgap engineering in Si (high speed + low cost + integration)
  - SiGe ideally suited for RF, analog, and digital circuits
  - BiCMOS gives many system-on-a-chip possibilities
- **SiGe For Extreme Temperatures**
  - all properties improve down to 77K (and below)
  - works fine up to 300C
- **SiGe For The Radiation Environment**
  - epi-base structure has built-in total-dose hardness
  - SEE mitigation approaches currently being pursued

SiGe Is Very Promising for Extreme Environments!
Now Is The Time For Focused Research In This Area!